ELECTRIC POWER GRID RELIABILITY EVALUATION

MODELS AND METHODS

CHANAN SINGH | PANIDA JIRUTITIJAROEN
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Library of Congress Cataloging-in-Publication Data is available.

ISBN: 9781119486275

Cover design: Wiley
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Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

To Our Parents

The late Sadhu Singh and the late Pritam Kaur
Pairat Jirutitijaroen and Karuna Jirutitijaroen
Ajoy Kumar Mitra and Jharna Mitra

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Preface

Over the past many years, the electric power grid has gone through transformative changes. This has been driven by the need to reduce carbon emissions, have more monitoring to improve situational awareness and provide more choices and participative ability to the customers. The net result is that the grid is becoming more complex. Whereas the increased intelligence and capabilities built into the system provide opportunities for operating the grid in innovative ways that were not available earlier, they also introduce new possibilities of more problems resulting in possibilities of more widespread failures.

The power grid is an infrastructure that develops with time and involves decision-making that may be irreversible most of the time. For example, building a transmission line or a wind or solar farm are not things that one can undo or change easily. So calculations to simulate the function of the new facilities and how they will affect the overall system has always been a part of the planning and operation of power systems. It is for this reason that sophisticated analysis and simulation tools have been a part of these processes, and these tools have been going through transformations over time to suit new realities.

The same is true about the reliability analysis of power grid. The quantitative reliability evaluation makes it possible to do appropriate trade-offs with cost, emissions and other factors, resulting in a rational decision-making. The tools for power system reliability analysis have been evolving over time as more computational power has become available.

The material in this book has evolved through our teaching graduate and undergraduate classes to our students primarily at Texas A&M, Michigan State and National University of Singapore. The material has also been taught in short courses at industry and other academic institutions. The choice and presentation of material is informed by our belief that a strong background in fundamentals is essential to understanding, properly adopting and improving the algorithms needed for reliability analysis. This is all the more important as the power system becomes more complex and its basic nature changes due to integration of renewable energy resources. More innovations in computational methods will be required as the need develops for adapting to new situations.

The material in this book is divided into two parts. The first part provides the theoretical foundations, covering a review of probability theory, stochastic processes and a frequency-based approach to understanding stochastic processes. These ideas are explained by using examples that connect with the power systems. Then both generic analytical and Monte Carlo methods are described. This first part can serve as material for a reliability course in general. The second part describes algorithms that have been developed for the reliability analysis of the power grid. This covers generation adequacy methods, and multinode analysis, which includes both multiarea as well as composite power system reliability evaluation. Then there are two chapters, one illustrating utilization of this material in energy planning and the second on integration of renewable resources that are characterized by their intermittent nature as energy sources.

Chanan Singh
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Acknowledgments

Many have contributed to this book in various ways, and we owe them a debt of gratitude.

Many of our students have contributed by attending our lectures, providing feedback and participating in the research that resulted in some of this material. It would be hard to thank them individually, so we thank them all as a group. We have also learned much by interacting with and following the work of our peers and other researchers and practitioners in the field, and we thank them all for enriching our expertise.

Last but not least, we would like to thank our families for their inspiration, support and patience while we were writing this book: our spouses Gurdeep, Wasu, and Padmini, our children Khenu Singh, Praow Jirutitijaroen, Ranadeep Mitra, Rukmini Mitra and Rajdeep Mitra, and grandchildren Kiran Parvan Singh and Saorise Vela Singh.

Chanan Singh
Panida Jirutitijaroen
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PART I

Concepts and Methods in System Reliability

1

Introduction to Reliability

1.1 Introduction

The term reliability is generally used to relate to the ability of a system to perform its intended function. The term is also used in a more definite sense as one of the measures of reliability and indicates the probability of not failing by the end of a certain period of time, called the mission time. In this book, this term will be used in the former sense unless otherwise indicated. In a qualitative sense, planners and designers are always concerned with reliability, but the qualitative sense does not help us understand and make decisions while dealing with complex situations. However, when defined quantitatively it becomes a parameter that can be traded off with other parameters, such as cost and emissions.

There can be many reasons for quantifying reliability. In some situations, we want to know what the reliability level is in quantitative measures. For example, in military or space applications, we want to know what the reliability actually is, as we are risking lives. In commercial applications, reliability has a definite trade-off with cost. So we want to have a decision tool for which reliability needs to be quantified. The following example will illustrate this situation.

Example 1.1 A system has a total load of 500 MW. The following options are available for satisfying this load, which is assumed constant for simplicity:

5 generators, each with 100 MW;
6 generators, each with 100 MW;
12 generators, each with 50 MW.

The question we need to answer in terms of design and operation aspect is: *Which of these alternatives has the best reliability?*

A little thinking will show that there is no way to answer this question without some additional data on the stochastic behavior of these units, which are failure and repair characteristics. After we obtain this data, models can be built

Electric Power Grid Reliability Evaluation: Models and Methods, First Edition. Chanan Singh, Panida Jirutitijaroen, and Joydeep Mitra.
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to quantify the reliability for these three cases, and then the question can be answered.

1.2 Quantitative Reliability

Most of the applications of reliability modeling are in the steady state domain or in the sense of an average behavior over a long period of time. If we describe the system behavior at any instance of time by its state, the collection of possible states that the system may assume is called the *state space*, denoted by S.

In reliability analysis, one can classify the system state into two main categories, success or failure states. In success states the system is able to do its intended function, whereas in the failed states it cannot. We are mostly concerned with how the system behaves in failure states. The basic indexes used to characterize this domain are as follows.

Probability of failure

Probability of failure, denoted by p_f, is the steady state probability of the system being in the failed state or unacceptable states. It is also defined as the long run fraction of the time that system spends in the failed state. The probability of system failure is easily found by summing up the probability of failure states as shown in (1.1):

$$p_f = \sum_{i \in Y} p_i, \tag{1.1}$$

where

p_f system unavailability or probability of system failure;
Y set of failure states, $Y \subset S$;
S system state space.

Frequency of failure

Frequency of failure, denoted by f_f, is the expected number of failures per unit time, e.g., per year. This index is found from the expected number of times that the system transits from success states to failure states. As will be seen clearly in Chapter 4, this index can be easily obtained by finding the expected number of transitions across the boundary of subset Y of failure states.

Mean cycle time

Mean cycle time, denoted by T_f, is the average time that the system spends between successive failures and is given by (1.2). This index is simply the reciprocal of the frequency index:

$$T_f = \frac{1}{f_f}. \tag{1.2}$$

Mean down time

Mean down time, denoted by T_D, is the average time spent in the failed states during each system failure event. In other words, this is the expected time of stay in Y in one cycle of system up and down periods. This index can be found from (1.3):

$$T_D = \frac{p_f}{f_f}. \tag{1.3}$$

Mean up time

Mean up time, denoted by T_U, is the mean time that the system stays in the up states before system failure and is given by (1.4):

$$T_U = T_f - T_D. \tag{1.4}$$

There are several other indices that can be obtained as a function of the above indices, and these will be discussed in Chapter 5.

There are also applications in the time domain, say $[0, T]$. For example, at time 0, we may be interested in knowing the probability of not having sufficient generation at time T in helping decide the start of additional generation. The following indices could be used in such situations:

1. Probability of failure at time T
   This indicates the probability of being in the failed state at time T. This does not mean that the system did not fail before time T. The system may have failed before T and repaired, so this only indicates the probability of the system being in a failed state at time T.
2. Reliability for time T
   This is the probability that the system has not failed by time T.
3. Interval frequency over $[0, T]$
   This is the expected number of failures in the interval $[0, T]$.
4. Fractional duration
   This is the average probability of being in the failed state in interval $[0, T]$.

The most commonly computed reliability measures can be categorized as three indices as follows.

1. Expected value indexes: These indices involve
   Expected Power Not Supplied (EPNS) or Expected Unserved Energy (EUE).
2. Probability indices such as
   Loss of Load Probability (LOLP) or Loss of Load Expectation (LOLE).
3. Frequency and duration indices such as
   Loss of Load Frequency (LOLF) or Loss of Load Duration (LOLD).

1.3 Basic Approaches for Considering Reliability in Decision-Making

Having quantified the attributes of reliability, the next step is to see how it can be included in the decision process. There are perhaps many ways of doing it, but the most commonly used are described in this section. It is important to remember that the purpose of reliability modeling and analysis is not always to achieve higher reliability but to attain the required or optimal reliability.

Reliability as a constraint

Reliability can be considered a constraint within which other parameters can be changed or optimized. Until now this is perhaps the most common manner in which reliability considerations are implemented. For example, in generation reliability there is a widely accepted criterion of loss of load of one day in 10 years.

Reliability as a component of overall cost optimization

The conceptual relationship between cost and reliability can be appreciated from Figure 1.1. The overall cost is a combination of the investment cost and the cost of failures to the customers. The investment cost would tend to increase if we are interested in higher levels of reliability. The cost of failures to the customers, on the other hand, tends to decrease with increased level of reliability. If we combine these costs, the total cost is shown by the solid curve, which has a minimum value. The reliability at this minimum cost may be considered an optimal level; points to the left of this would be dominated by customer dissatisfaction, while points to the right may be dominated by investment cost considerations.

It can be appreciated that in this type of analysis we need to calculate the worth of reliability. In other words, how much do the customers think that

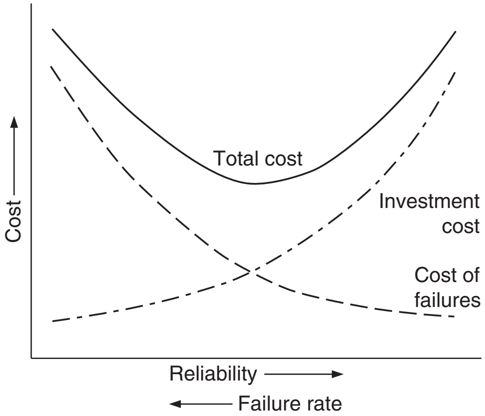

Figure 1.1 Trade-off between reliability and cost.